



Large Scale Production of Densified Hydrogen to the Triple Point and Below

**Adam Swanger¹, Bill Notardonato¹, James Fesmire¹
Kevin Jumper¹, Wesley Johnson² and Tom Tomsik²**

¹NASA Kennedy Space Center, Cryogenics Test Laboratory, KSC, FL 32899 USA

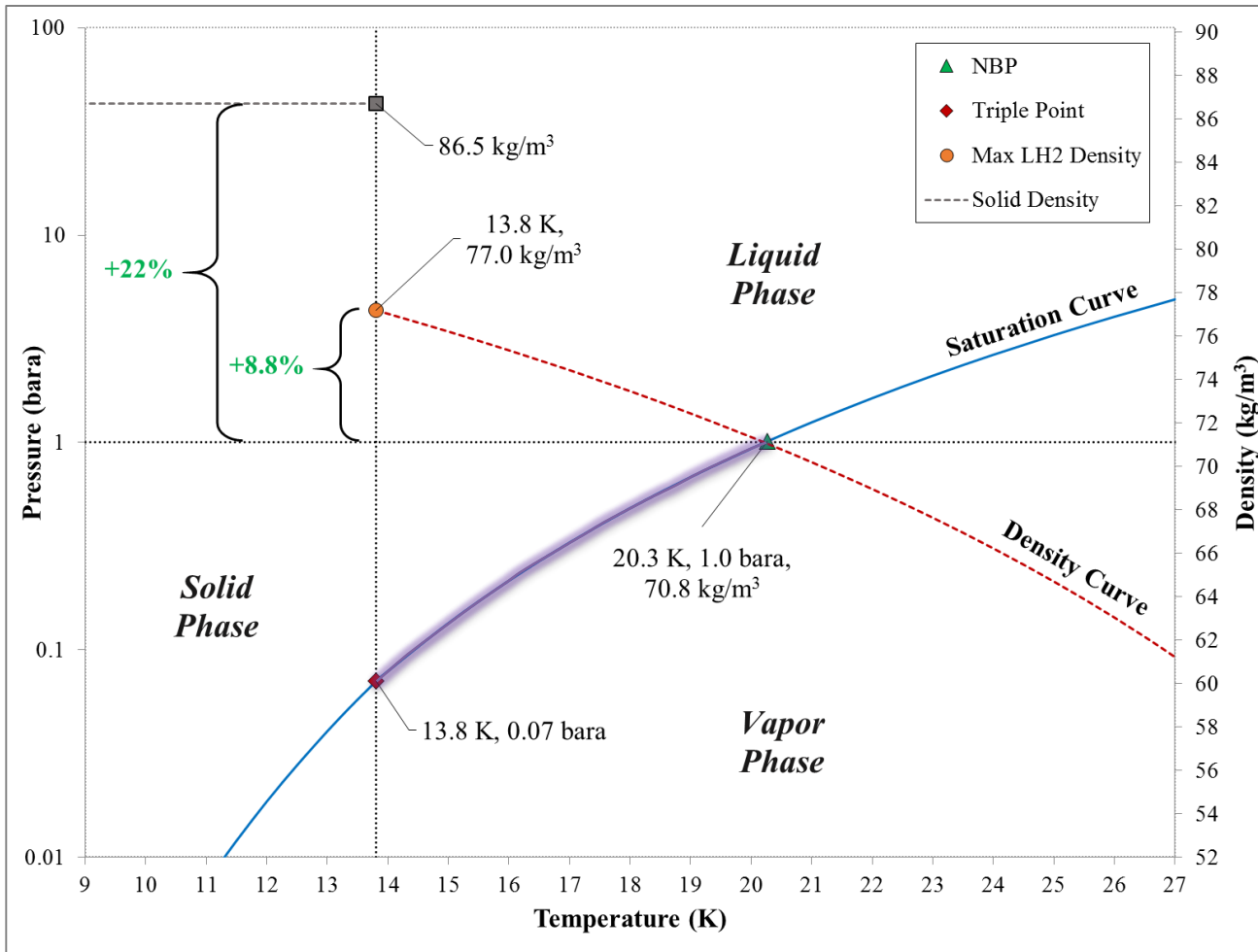
²NASA Glenn Research Center, Cleveland, OH 44135 USA

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Densification Benefits



Properties of para-hydrogen from RefProp Version 8

- Additional payload to orbit of 4.9% to 17.5% for liquid, up to 26% for slush
- Enables advanced capabilities such as reusability (SpaceX Falcon 9)



Image Credit: Google

- Additional energy storage capacity and enthalpy margin

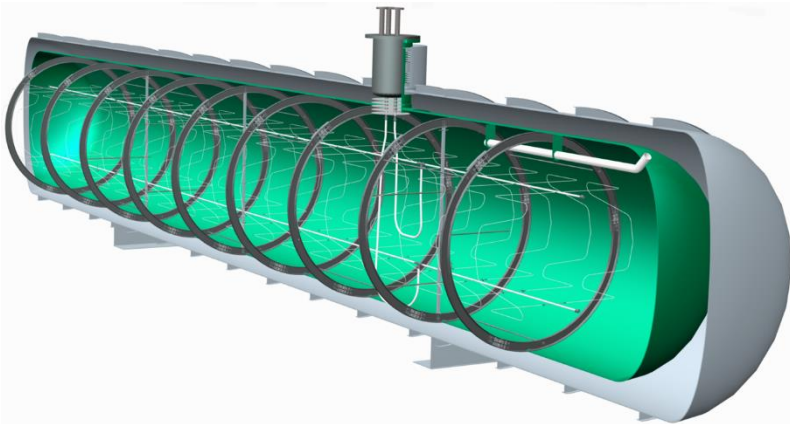
Densification History Snapshot



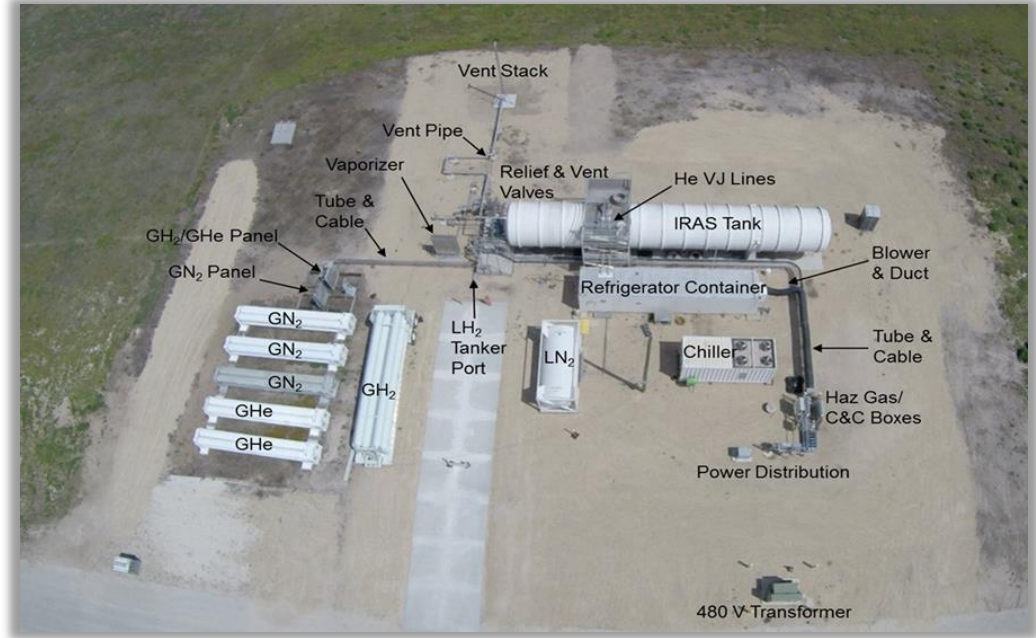
NASA/USAF has investigated use of densified LOX/LH₂ since the 1960's

- 1960's NBS quantifies densified and slush hydrogen thermodynamic properties
- 1977 Martin Marietta report on SSTO using densified LOX and LH₂
- **1988-1994** NASP X-30 Slush Hydrogen Technology Program—large scale production, transfer and in tank thermodynamics
- 1995-1997 LH₂ densification prototype system: 2 lb/sec rig tested at K-Site X-33 RLV Precursor Demo
- 1996 Hot fire ignition test of RL10B-2 engine with densified LH₂ at Plum Brook B2
- **1997- 2001** Design, build and test of large scale LOX & LH₂ propellant densification units for X-33/RLV
- 2000 STA Tank Loading Tests w/GRC 30 lb/sec LOX PDU at GRC S40
- 2001 LN₂ Performance Demo Tests w/GRC 8 lb/sec LH₂ PDU at GRC S40
- 2001 Space shuttle performance enhancement study with propellant densification – 8 mo. multi-center effort
- 2002-2006 LH₂ densification to 15K using 180 liter IRAS system with Florida Solar Energy Center (FSEC)
- 2002-2003 2nd GEN RLV Program—funded three densification technology demonstrators (PHPK, Sierra Lobo, and LM/Praxair)
- 2011 LOX subcooler installed at Wallops for Taurus II vehicle (first densified prop flight in USA)
- **2012-2016** GODU-LH2 system built and tested at NASA KSC—125,000 L LH₂ densifier using IRAS
- **2015-Present** SpaceX using densified LOX and RP-1, not to increase mass to LEO, but to enable reusability

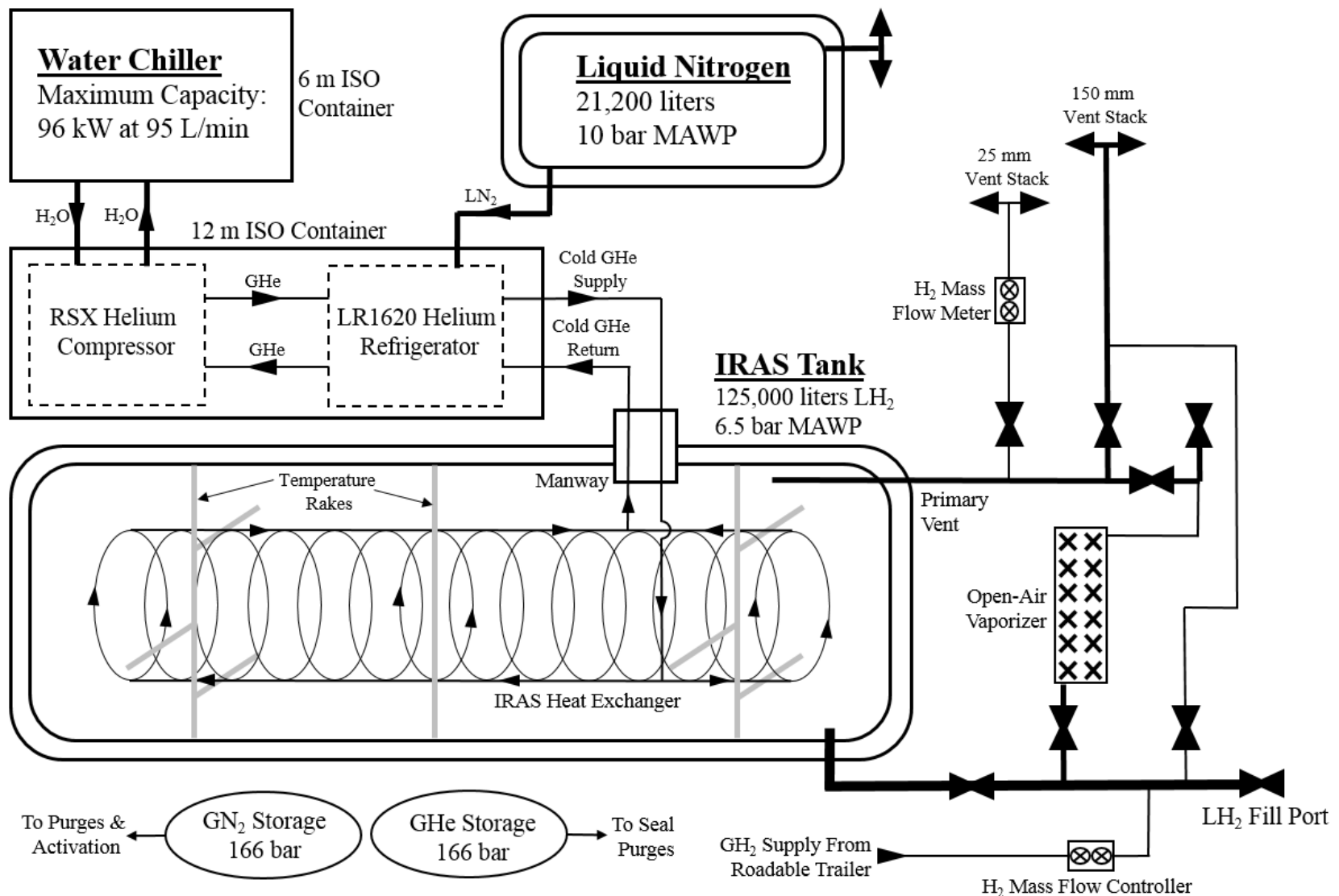
- Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) project began in 2012 to demonstrate:
 1. Zero loss storage and transfer of LH_2 at a large scale.
 2. Hydrogen **densification** in the storage tank
 3. Demonstrate in-situ hydrogen liquefaction
- System used Integrated Refrigeration and Storage (IRAS) approach
 - Interface a cryogenic refrigerator to a liquid hydrogen storage tank via an internal heat exchanger



GODU-LH2 System



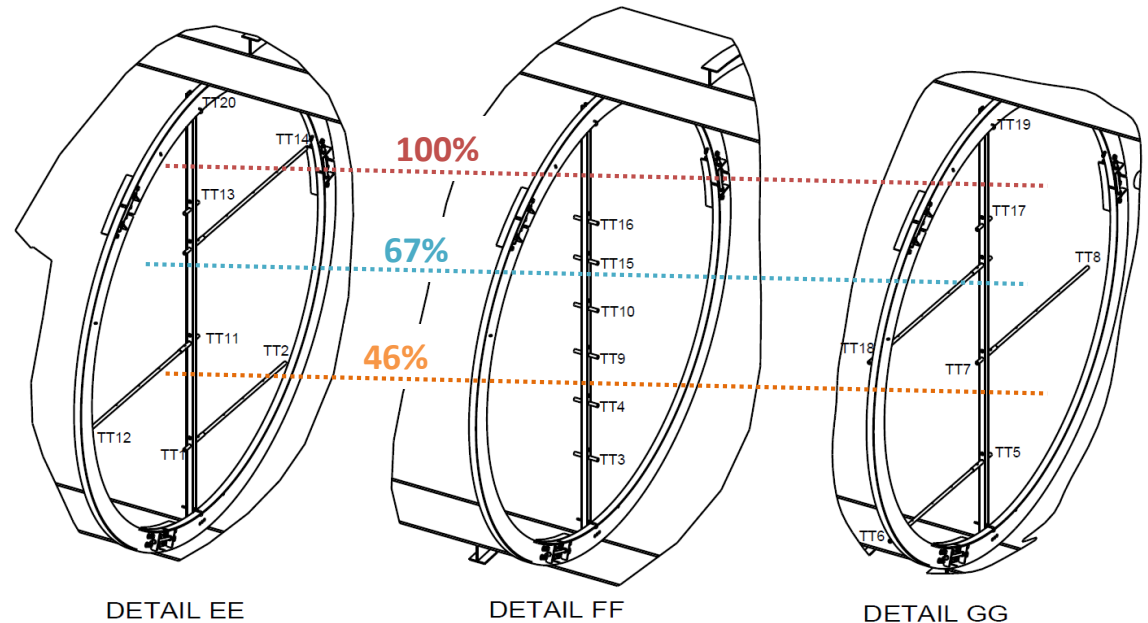
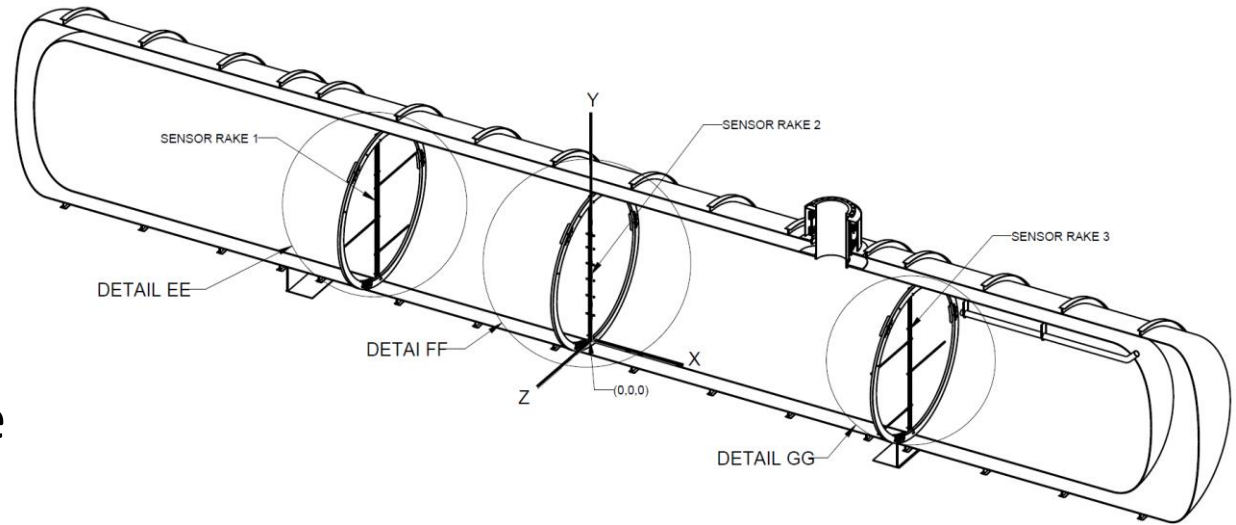
GODU-LH2 Functional Diagram



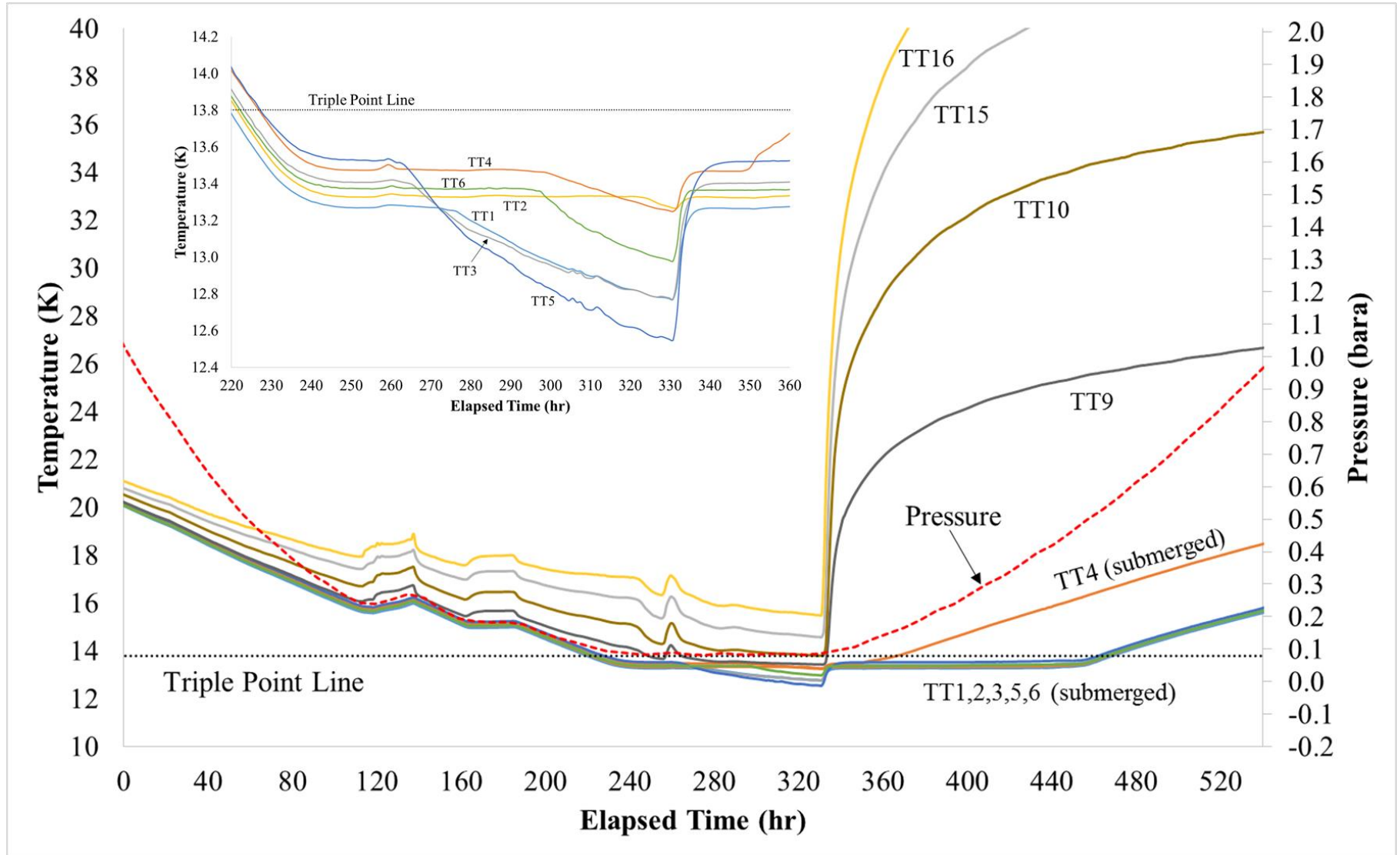
Densification Testing



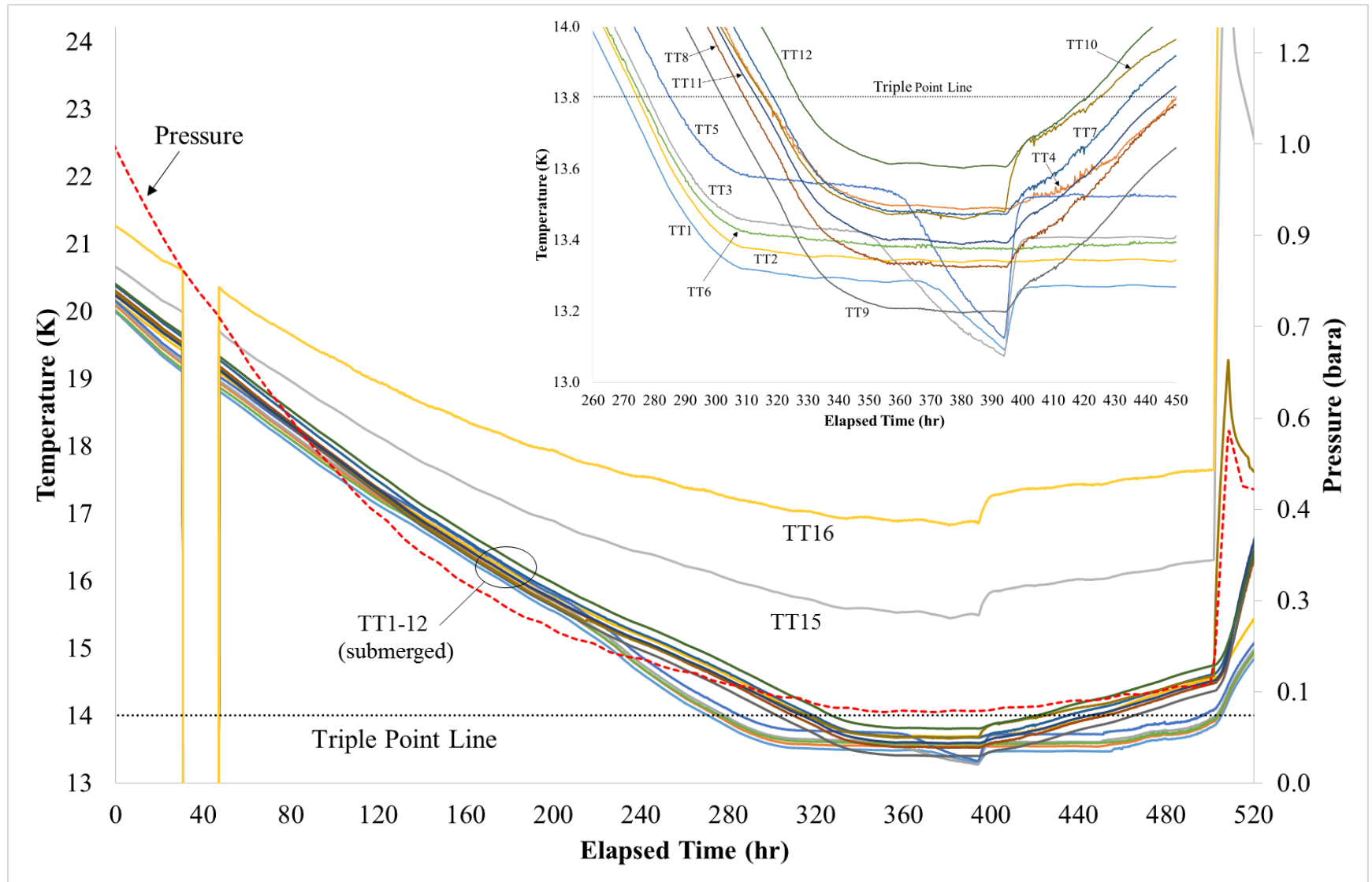
- Densification was conducted at three different fill levels: 46%, 67% and 100%
- At the lower fill levels LH₂ state hit the triple point, and slush was generated
- Temps were trending toward the TP at 100% also, but ran out of time in the schedule



46% Full Test Results



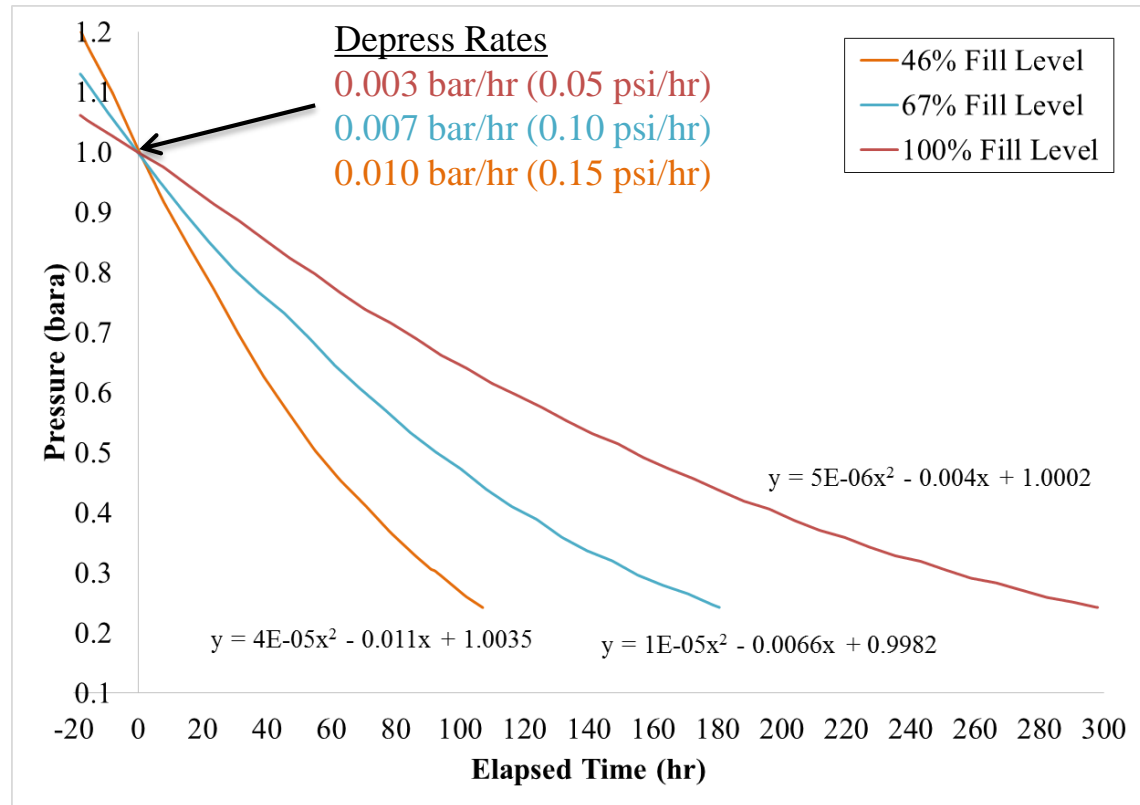
67% Full Test Results



Summary of Results



- **100%** full test was cut short prior to reaching the triple point
 - Densified 125,000 L of LH₂ to 15.5 K in 300 hours
- **67%** test densified 83,750 L to the triple point in roughly 300 hours
- **46%** test densified 57,500 L to the triple point in 240 hours
 - Estimated 1,020 kg of ice was generated, or 25% solid-to-liquid mass fraction



Max Refrigeration Ratio at NBP

$$\left(\frac{\dot{Q}_{\text{lift}}}{\dot{Q}_{\text{tank}}} \right)_{\text{NBP}} \approx 3.0 \text{ to } 3.4$$

Summary of Results—Lingering Questions



1. Why was the local triple point of the diodes consistently below the official triple point of pure para-hydrogen?

- On average they were 0.42 K lower
- Pressure was very close, but slightly above the TP, within 0.002 bar
- All fell below the NBP during boil-off testing also (0.18 K lower on average)

✓ Current thoughts are instrumentation bias and/or binary mixture effects....

2. How did some diodes begin to measure sub-triple point temperatures after having been at that condition for a lengthy period of time?

- Almost all sub-TP measurements were below the bottom heat exchanger manifold (i.e. the inlet), at an elevation of 0.57 m (22.4")
- Phenomenon happened at the 46% and 67% fill levels, and seemed to evolve in time down the length of the tank, and radially outwards

✓ Current thoughts are supercooling of the liquid/slush mixture under the HX....

3. Where was the solid H₂ forming & residing: did it adhere to the SS tubes or sink to the bottom of the tank? Was it a bulk slush mixture, or was there a layer of hydrogen “snow” at the bottom of the tank?

Conclusion



- The GODU-LH2 system successfully completed all of its densification test objectives, and exceeded performance expectations by producing slush hydrogen at two different fill levels
- IRAS has been demonstrated to be able to produce batches of DH_2 or SH_2 on scales relevant to launch facilities
- Created, **POSSIBLY**, the largest quantity of solid hydrogen in history

Future Plans

- Transport system to rocket test stand and perform DH_2 engine test
- Perform DH_2 loading test with flight-like tank
- Switch over to LNG or methane to test IRAS for future operations
- Package system into a **fully transportable, 900 W @ 20 K DC cycle cryocooler** for multi-customer functionality

Thank You For Your Time!

Questions?



Storm clouds over the GODU-LH2 test site—June 30th 2016